



**Department of Energy**  
Germantown, MD 20874-1290

**Safety Evaluation Report**

**FERMCO Ingot Sections in the Rev. L SARP of  
the Steel Banded Wooden Shipping Containers (SBWSC),**

**Docket No. 00-27-5467**

**Background**

The criticality confirmatory evaluation in this Safety Evaluation Report (SER) addresses the FERMCO Ingot Sections (3 types) described in the Rev. L SARP for the Steel Banded Wooden Shipping Containers (SBWSC). The FERMCO Ingot Sections are unirradiated, low enrichment (1.256 wt.% U-235 max.) cylindrical uranium ingots with the following outer diameters (OD) and lengths (L): 33.2 cm OD x 7.6 cm L (13 in. D x 3 in. L), 33.2 cm OD x 15.2 cm L (13 in. OD x 6 in. L), and 25.4 cm OD x 7.6 cm L (10 in. OD x 6 in. L). The SARP proposes to ship the FERMCO Ingot Sections in the SBWSC Model G-4214 or G-4292, with each containing four or two ingot sections in an exclusive use shipment.

The staff reviewed the criticality analyses presented in the SARP and performed independent confirmatory evaluation of criticality safety for the FERMCO Ingot Sections. The staff confirmed that the Transport Index (TI), and the number of packages proposed in the Rev. L SARP for the FERMCO Ingot Sections in an exclusive use shipment, meet the criticality safety requirements of 10 CFR Part 71 under normal conditions of transport (NCT) and hypothetical accidents (HAC).

Other safety aspects (i.e., general information, structural, thermal, shielding, containment, operating procedures, acceptance tests and maintenance, and quality assurance) of the SBWSC have been reviewed for similar types of payloads in Rev G through L of the SARP and documented in the Safety Evaluation Reports (SER) for the Rev. 11 through Rev. 15 of the CoC. The conclusions obtained in the earlier evaluation and SERs for the other safety aspects of the SBWSC remain valid and applicable to the payloads evaluated in this SER and will not be repeated.

**Criticality Safety Evaluation**

No special feature is incorporated in the design of the SBWSC for criticality control. To comply with 10 CFR Part 71, criticality safety must be demonstrated for a fissile material package under NCT and HAC. The hypothetical accidents consist of a sequence of events (e.g., vertical drops, fire, and immersion in water) that would damage the package and thus often represent a more limiting condition for criticality safety analysis, i.e., 2xN damaged array analysis where N is the number of packages in the array according to 10 CFR 71.59. In the criticality analysis for the SBWSC, the applicant conservatively assumed that all SBWSC in a shipment are burned during the 30-minute hypothetical accident fire (even though the wooden boxes are most likely only charred), and that the ingot sections are "scattered and arranged" in the most reactive



configuration with interspersed hydrogenous moderation and total water (30 cm) reflection, as required by 10 CFR 71.55 and 10 CFR 71.59. The staff confirmed that the applicant has indeed established the most reactive configuration for the number of ingot sections (and packages) allowed in a shipment that would remain subcritical with an adequate safety margin. Once the allowable number of ingot sections is obtained, the number of packages per shipment  $N$  can be determined based on the number of ingot sections per package, and the minimum TI for criticality control in a shipment is calculated as  $TI = 50/N$ . For an exclusive-use shipment as requested for the SBWSC, the sum of TI must be limited to 100 per 10 CFR 71.59.

#### Determination of Optimal Lattice Parameters and the Most Reactive Configuration

Determination of the maximum allowable number of ingot sections under the most reactive configuration begins with a search for the optimal lattice parameters, i.e., pitch, axial gap, and moderator density, that would maximize the reactivity, i.e., neutron multiplication factor ( $k_{\infty}$ ) for an infinite array of ingot sections in a close-packed, hexagonal lattice. The staff found that for a given uranium ingot composition and geometry, the  $k_{\infty}$  is mainly influenced by the amount of water in the unit cell for the hexagonal lattice configuration. Consequently, a loosely packed array with a relatively large pitch and axial gap and low moderator density can have a mass ratio of fissile to moderator material similar to that of a tightly packed array with a smaller pitch and axial gap, but higher moderator density. Infinite arrays of ingot sections having these two types of lattice parameters will have comparable  $k_{\infty}$  values, and thus can be regarded as equally reactive configurations. Determination of the most reactive configuration, therefore, must consider the effect of neutron leakage, which exists only for a finite array of ingot sections.

Because neutron leakage from a system reduces reactivity, the most reactive configuration for a finite array of ingot sections must be one with a minimum surface-to-volume ratio that gives the smallest total surface area for neutron leakage. A tightly packed array within a spherical enclosure and with total water reflection, therefore, should minimize neutron leakage. The staff has developed the necessary framework for determining the radius of the spherical enclosure for the finite array using iterative MCNP calculations (See "Criticality Control in Shipments of Fissile Material," J. R. Liaw and Y. Y. Liu, Proc. ANS Topical Meeting on Spent Fuel and Fissile Material Management, San Diego, CA., June 5-8, 2000, pp. 347-352.) The most reactive configuration of the finite array (and the maximum number of ingot sections allowed in a shipment) is determined when the adjusted effective neutron multiplication factor ( $k_{adj}$ ) for the  $2xN$  damaged array satisfies the following criterion,

$$k_{adj} = k_{eff} + 0.00258 + 2(0.006^2 + \sigma^2)^{0.5} \leq 0.95,$$

where  $k_{eff}$  and  $\sigma$  are the effective neutron multiplication factor and uncertainty, respectively, obtained in the MCNP calculations. The other constants in the equation are the code bias (0.00258) and uncertainty (0.006) obtained from benchmark calculations against the critical experiments. This is the same formula used by the applicant in the SARP, and the formula is consistent with that recommended in NUREG/CR-5661, "Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packages," April 1997.

Determination of Transport Index and Maximum Number of Packages per Shipment

The applicant followed the above procedure and determined the radius of spherical enclosure for finite arrays of each FERMCO Ingot Section based on  $k_{adj} \leq 0.95$ . The amount of fissile material within the spherical enclosure is the "maximum subcritical mass" listed in the SARP (4,312 kg, 12,144 kg, and 7,073 kg for the FERMCO Ingot Section of 13 in. OD x 3 in. L, 13 in. OD x 6 in. L, and 10 in. OD x 6 in. L, respectively) that meets the 10 CFR 71.59 criticality safety requirements. The applicant determined the allowable number of FERMCO Ingot Sections by dividing their "maximum subcritical mass" by the mass of each FERMCO Ingot Section (123.7 kg, 247.4 kg, and 146.4 kg for the 13 in. OD x 3 in. L, 13 in. OD x 6 in. L, and 10 in. OD x 6 in. L, respectively). The resulting number of ingot sections then determines the number of packages (2xN) per shipment depending on the number of ingot sections loaded per package. By definition, the TI for criticality control is  $TI = 50/N$ , and the sum of TI of all packages should be less than 100 in an exclusive use shipment.

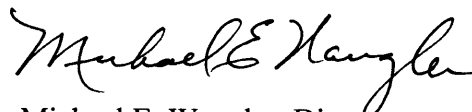
Table 1 below gives the minimum TI values and other pertinent information for the three FERMCO Ingot Sections in the designated SBWSC Model. The last two columns in Table 1 give the  $k_{adj}$  values from the SARP and the staff's independent confirmatory analysis for each FERMCO Ingot Section with 1.256 wt.% U-235 enrichment. Each confirmatory  $k_{adj}$  represents a set of MCNP calculations with lattice parameters varied to verify the most reactive configuration for the finite arrays of the ingot sections. The differences between the  $k_{adj}$  values for each FERMCO Ingot Section (0.002 to 0.005) in Table 1 are insignificant as they are of the same order of the code bias (0.00258) and uncertainty (0.006) obtained in the benchmark calculations against the critical experiments. The staff has thus independently confirmed that the  $k_{adj}$  values for the FERMCO Ingot Sections meet the subcriticality criterion of  $\leq 0.95$ .

Table 1. Transport Index (TI) for Criticality Control  
for the FERMCO Ingot Sections in the SBWSC (Rev.L SARP)

Size Section OD x L, cm(in)	SBWSC Model	No. Ingot Sections/ SBWSC	$k_{adj}$		Minimum Transport Index
			SARP	Staff	
33.2 x 7.6 (13 x 3)	G-4214 or G-4292	4	0.9422	0.94759	11.5
33.2 x 15.2 (13 x 6)	G-4214 or G-4292	2	0.9385	0.94159	4.1
25.4 x 15.2 (10 x 3)	G-4214 or G-4292	2	0.9406	0.94285	4.1

Summary

The staff has evaluated the criticality safety analyses presented in the SARP for the FERMCO Ingot Sections. The staff has performed independent calculations and confirmed that the minimum TI values (and the corresponding maximum number of packages) for the FERMCO Ingot Sections listed in the Rev. L SARP are conservative and meet the 10 CFR Part 71 requirements under NCT and HAC. The FERMCO Ingot Sections (with 1.256 wt.% U-235 max.) can thus be safely packaged and transported in the designated models of the SBWSC in an exclusive use shipment.



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Date: **SEP 26 2000**.